CONSTRAINTS ON THE MASS AND RADIUS OF PULSARS FROM X-RAY OBSERVATIONS OF THEIR POLAR CAPS

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The properties of X-ray radiation from the polar caps predicted by the radio pulsar models depend on the surface chemical composition, magnetic field and star's mass and radius as well as on the cap temperature, size and position. Fitting the radiation spectra and light curves with the neutron star atmosphere models enables one to infer these parameters. We present here results obtained from the analysis of the soft X-ray radiation of PSR J0437-4715. In particular, with the aid of radio polarization data, we put constraints on the pulsar mass-to-radius ratio.

1 Introduction

Current models of radio pulsars [1,2,3] predict a typical polar cap (PC) size $R_{\rm pc} \sim (2\pi R^3/Pc)^{1/2}$ and PC temperatures $T_{\rm pc} \sim 3\times10^5 - 6\times10^6$ K, depending on the model adopted. The spectra of the thermal PC radiation are mainly determined by the temperature, gravitational acceleration, magnetic field and chemical composition of emitting layers (atmospheres). The light curves of the pulsed PC radiation depend not only on the orientation of the magnetic and rotation axes, but also on the magnetic field and chemical composition which affect the angular distribution of radiation, and the neutron star (NS) mass-to-radius ratio, M/R, which determines the gravitational bending of the photon trajectories. The best candidates for the investigation of the PC radiation are nearby, old pulsars for which both the nonthermal radiation from relativistic particles and thermal radiation from the entire NS surface are expected to be negligibly faint. Here we report results obtained for PSR J0437–4715 ($P =$ 5.75 ms, $\tau = P/2\dot{P} = 5 \times 10^9$ yr, $B \sim 3 \times 10^8$ G, $d \approx 180$ pc). *ROSAT* observations of this object have revealed [4] smooth pulsations with the pulsed fraction $\sim 25 - 50\%$ growing with the photon energy. Such behavior has been predicted [5] for the radiation emergent from the NS atmospheres with low magnetic fields $B < 10^{10}$ G. Making use of the low-field NS atmosphere models [5], we model PC radiation with allowance for the gravitational effects [6] and compare the results with observational data.

Figure 1: NS mass-radius diagram with the lines of constant values of M/R (the numbers in units of $M_\odot/10$ km) and the $M(R)$ curves for soft (π) and hard (TI and MF) equations of state of superdense matter [10]. The shaded region indicates the mass-radius domain compatible with $\zeta = 40^\circ$ and $\alpha = 35^\circ$.

2 Results

Our analysis has shown [7] that both the spectra and the light curves obtained with *ROSAT* and *EUVE* can be interpreted as thermal radiation from two PCs with radii $R_{\rm pc} = 0.8 - 0.9$ km (comparable to 1.9 km expected from the simple estimate) covered with hydrogen or helium at a temperature $T_{\rm pc} = (8-9) \times 10^5$ K. Neither the blackbody nor iron atmosphere models give acceptable spectral fits. Those results were obtained for fixed $M = 1.4 M_\odot$ and $R = 10$ km, and the angles between the pulsar rotation axis and the line of sight, $\zeta = 40^\circ$, and between the rotation and magnetic axes, $\alpha = 35^\circ$, evaluated from the phase dependence of the radio polarization position angle [8]. We checked that these parameters do not affect significantly the results of the spectral fits (PC temperature and size). However, the values of α, ζ and M/R drastically affect the shape of the light curve and the pulsed fraction.

To constrain these parameters, we (i) fitted the *ROSAT* PSPC count rate spectrum with the hydrogen atmosphere models on a grid of ζ, α and M/R values and obtained the corresponding set of $R_{\rm pc}$ and $T_{\rm pc}$; (ii) used this set to compute the model *ROSAT* PSPC light curves and evaluated their deviations (χ^2 values) from the observed light curve; (iii) calculated the confidence regions in the ζ-α plane at trial values of M/R. If there were no observational

information about the α, ζ values, the only constraint on the M/R ratio would be $M < 1.6M_{\odot}(R/10\text{ km})$, or $R > 8.8(M/1.4M_{\odot})$ km, at the 99% confidence level. If, however, we adopt $\zeta = 40^{\circ}$ and $\alpha = 35^{\circ}$, the M/R ratio lies in the range $1.4 < (M/M_{\odot})/(R/10\text{ km}) < 1.6$ (Fig. 1). This means that if the pulsar mass is $M = 1.4M_{\odot}$, its radius is in the range $R = 8.8 - 10.0$ km. An alternative set of angles[9], $\zeta = 24^{\circ}$ and $\alpha = 20^{\circ}$, yields $(M/M_{\odot})/(R/10\text{ km}) < 0.3$, leading to very low masses, $M < 0.5M_{\odot}$, at any R allowed by the equations of state.

Thus, the analysis of the PC X-ray radiation in terms of the NS atmosphere models provides a new tool to constrain the NS mass and radius and the equation state of the superdense matter. A similar analysis of X-ray radiation from pulsars with strong magnetic fields, $B \sim 10^{12}$ G (e. g., PSR B1929+10) would enable one to additionally constrain the magnetic field strength.

Acknowledgments

The work was partially supported through the NASA grant NAG5-2807, INTAS grant 94-3834 and DFG-RBRF grant 96-02-00177G. VEZ acknowledges the Max-Planck fellowship.

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